Preprint
UCRL-JC-138734

Characterization of Thermal Sprayed Aluminum and Stainless Steel Coatings for Clean Laser Enclosures

R. Chow, T. A. Decker, R. V. Gansert, and D. Gansert

This article was submitted to
Materials Information Society Materials Solutions Conference and Exposition 2000
St. Louis, MO
October 9-12, 2000

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

April 6, 2000

Characterization of Thermal Sprayed Aluminum and Stainless Steel Coatings for Clean Laser Enclosures

Dr. Robert Chow, Materials Science Engineer, (Chow3@llnl.gov)
Mr. Todd A. Decker, Mechanical Engineer, (Decker4@llnl.gov)
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550
925-422-7615, 925-422-1210 (fax)

Dr. Robert V. Gansert, R&D Director (Bgansert@hardfacealloys.com)
Mr. Daren Gansert, President (Dgarsert@hardfacealloys.com)
Hardface Alloys, Inc.
9230 Norwalk Way
Sante Fe Springs, CA 90670
562-463-8133, 562-463-8143 (fax)

ABSTRACT

Surfaces of steel structures that enclose high-fluence, large-beam lasers have conventional and unconventional requirements. Aside from rust prevention, the surfaces must resist laser-induced degradation and the contamination of the optical components. The latter requires a surface that can be precision cleaned to low levels of particulate and organic residue. In addition, the surface treatment for the walls should be economical to apply because of the large surface areas involved, and accommodating with intricate joint geometries. Thermal sprayed coatings of aluminum (Al) and stainless steel are candidate surface materials. Coatings are produced and characterized for porosity, smoothness, and hardness. These properties have a bearing on the cleanliness of the coating. The laser resistance of Al and 316L coatings are given. The paper summarizes the characterization of twin-wire-arc deposited Al, high-velocity-oxygen-fueled (HVOF) deposited Al, flame-sprayed 316L, and HVOF deposited 316L. The most promising candidate coating is that of HVOF Al. This Al coating has the lowest porosity (8%) compared the other three coatings and relatively low hardness (100 VHN). The as-deposited roughness (Ra) is 433 μinches, but after a quick sanding by hand, the roughness decreased to 166 μinches. Other post-coat treatments are discussed.

HVOF aluminum coatings are demonstrated. Al coatings are corrosion barriers for steel, and this work shows promising resistance to laser damage and low particulation rates.

Keywords: Porosity, Hardness, Post-treatment

INTRODUCTION

One alternative for the enclosure of large, high-fluences laser beams is simply steel because of cost and design flexibility from the numerous variety of structural members available. Trailer-truck sized frames are fitted together, forming the infrastructure of main laser cavity. Various pre-assembled optical units for the amplification and transport of the laser beam are kinematically mounted onto the frames. Intense short-wavelength flash-lamp pump light and stray light from the amplified laser beam illuminate the interior portions of these steel infrastructures. Photons from these illumination sources are readily absorbed by steel and it's oxides, namely rust. The deleterious nature of the light absorption to the operation of the laser starts with the rust particulates that would be ejected from the steel walls. Over time, the rust particulates would eventually diffuse to and contaminate the high performance optics contained in the pre-assembled units. Upon the subsequent laser pulse, the rust would absorb light, transfer heat to the optical surface, cause catastrophic mechanical damage to these optics even though the damage sites are sub-millimeter in length. The damage may even be propagated to transport optics further downstream due to diffraction effects. In order to control this optical damage scenario, the interior walls must be protected with material that is laser-resistant, and itself not be a source of any other contaminant to the optics [1].

Al and stainless steel have been determined to resist degradation via high laser fluence in comparison to other metals and organic coatings [2, 3]. In addition to the laser-resistance, an Al coating minimizes rust generation by acting as a cathodic protective coating. An inexpensive method of covering large surface areas of steel by Al is via thermal spray deposition processes. Typical field applications of thermal-sprayed Al (TSA) create rough, as-sprayed surfaces. An encapsulating organic cover, as conventionally applied over TSA in the field, is not acceptable due to hydrocarbon outgassing and contamination of the high performance optics. Uncoated, the roughness of the TSA surface act as particulate getters, making the aqueous precision cleaning [4] of these surfaces extremely difficult to achieve. As a further requirement, the surface treatment of the steel structures had to be cleaned to low levels (Level 100) for later assembly and operational purposes. In addition, the surface cleanliness had to be verified by a direct contact method [1,5].

The purpose of this report is to compare the thermal spray deposition of selected materials that may meet stated requirements. For comparison, Al coatings are deposited using an economical process tool, a twin-wire arc gun, and by a high-velocity oxy-fueled (HVOF) gun. Stainless steel deposition by a flame-spray tool and an HVOF gun are also studied. Since the as-deposited coatings may not to meet all of the cleanliness criteria, studies to treat the coating are also implemented.

THERMAL SPRAY DEPOSITION PROCESSES

All thermal spray processes produce coatings primarily by the rapid solidification process and secondarily by mechanical interaction with the substrate. In the Al twin-wire arc process, two consumable Al wire electrodes, insulated from each other, automatically advance to meet at a point in an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wire initiates an arc that melts the tips of the wire electrodes. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off molten droplets and forming the atomizing spray. The arc temperatures considerably exceed the melting point of the spray material. During the melting cycle of Al, the metal is super-heated to the point where some volatilization occurs. The spray is directed at the substrate to be coated.

Combustion flame spraying of 316L powder use guns (systems) that are lighter and more compact than the other types of thermal spray processes. Therefore these are the systems of choice for onsite work. Due to the lower particle velocities and temperatures obtained, the flame-sprayed coatings generally have lower adhesive strength, lower overall cohesive strength, and higher porosity than coatings produced by other spray processes. The selection of 316L material is to ameliorate these shortcomings.

While design differences exist between the commercially available HVOF systems, all contain an HVOF gun, gas control console, water-cooling unit, and powder feed unit. The source powder is fed into the combustion chamber, heated by convectively from the flame, and accelerated to high velocities by the drag forces associated with the exhaust gasses. In comparison, the HVOF process contributes the same order of magnitude of heating, but also imparts supersonic velocities to the powder. The resultant coating has greatly increased mechanical bonding and cohesive strengths.

A TAFA JP-5000 HVOF system is used to deposit the 316L powder and the Stellite Jet-Kote NOVA Lite (HVOF) system is used to deposit the Al powder. The combustion fuel is oxygen and C3H6. The diameter of the 316L is smaller than recommended by the hardware manufacturers, 58 μm. The diameter of the Al powder is chosen to be as small as commercially practical, 30 μm. The deposition of Al powder by the HVOF process is not performed on a routine basis and no citations could be located. The deposition of Al by an HVOF process has a much higher technical risk compared to the other coating evaluated in this report. The risks range come in the form of complete vaporization of the Al within the nozzle, pre-mature Al condensate build-up on the nozzle leading to clogging, and the complete oxidation of the Al powder such that no coating would adhere to the substrate. Another risk is that of operational cost, where the commercially available HVOF systems are not designed to handle low melting point metals and may require frequent maintenance cycles.

The benefits of the HVOF process for Al is two-fold. The HVOF combustion gas exhausts from the nozzle with supersonic velocities. The HVOF process ejects the source particles with much higher velocities than the other thermal spray processes. The added kinetic energy of the particles is expected to increase the adhesion and decrease the porosity of the deposited coating. Secondly, Al is softer than 316L so if post-coat treatment of the surface is required, the Al coating is expected to easier to smooth than a 316L coating.

The use of fine diameter powders is expected to produce smoother coatings than starting with larger powders or wire. Fine powders make smaller splats and these splats are easier to flatten by other incoming splats. Smaller splats minimize deposition shadowing which decreases the pore density and size.

The surface preparation had two considerations. First to provide an anchor-tooth texture for improved coating adherence, and second not to contribute unnecessary surface roughness. The 60-grit alumina blasting media was chosen. The grit was blasted at a pressure of 45 psi, normal to the surface.

CLEANLINESS VERIFICATION

Cleanliness verification is performed with hand-held tool. The Teflon tool was designed to clasp onto a 2 x 1 inch filter paper. The tool applies a uniform pressure onto the filter paper while the drywiping a surface in a 10 inch swath. The collection efficiency depends on the surface texture and cleanliness. For surfaces near the cleanliness levels of 100, the efficiency is estimated to be about 95%. A count of particles greater than 10 microns is conducted manually with a 60x inspection microscope and a flashlight illumination.

Figure 1 Fixture developed by LLNL to perform cleanliness verification. The fixture provides a method of holding the filter paper while folded around an elastomeric cushion approximately 6 mm wide and 50.8 mm long.

RESULTS AND DISCUSSIONS

As-deposited Coatings

The production of an Al coating by an HVOF process is successful. The productivity of the process is sufficient to provide tens of square inches of coating for morphological and post-coat finishing analysis. Characteristics of all the as-deposited coatings are summarized in Table 1.

Table 1 Roughness, hardness, and porosity of as-deposited thermal-sprayed coatings.

Thermal Spray Process	Deposited Mat'l	Mat'l Form	Roughness (μinches)	Microhardness (VHN)	Porosity (%)
Flame	Al	Wire	705 ± 85	Too porous	30 - 40
Flame	316L	Powder	398 ± 69	237 ± 11	19 - 24
HVOF	Al	Powder	433 ± 69	100 ± 12	8.0
HVOF	316L	Powder	428 ± 28	278 ± 12	12 - 14

The surface roughness is measured with a stylus gauge, where a roughness number is averaged from three scans made per sample. Scan lengths are 2 mm in length. Another indication of the surface roughnesses are observed in Fig. 2, a through d, the morphology of the twin-wire arc Al (TWA), HVOF Al, flame-sprayed (FS) 316L powder, and HVOF 316L coatings, respectively. As expected, the TWA Al has the roughest surface because of the wire-size and deposition mechanics. The eighth inch diameter wire creates much larger Al splats than that created by starting with fine Al powder sizes. The combination of a higher velocity thermal spray process and of finer material does result in much smoother surfaces. However, even these surfaces still tore the paper wipe used for collecting and in the counting of particulates. Figure 3 shows in cross-section, that all the surfaces contain splats protruding above the surface, acting as hooks for the paper-wipe.

Figure 2 As-deposited surface morphology from (a) Twin wire arc Al wire, 0.125" diameter; (b) HVOF of Al powder; (c) Flame-sprayed 316L stainless steel powder; (d) HVOF of 316L stainless steel powder.

Figure 3 Metallurgical cross-sections of (a) Twin wire arc coating, 0.007" thick, from Al wire, 0.125" diameter; (b) HVOF coating, 0.015" thick, from Al powder; (c) Flame-sprayed coating, 0.010" thick, from 316L stainless steel powder; (d) HVOF coating, 0.012" thick, from 316L stainless steel powder. Panels (a) and (b) have the coating on the right and the substrate on the left. Panels (c) and (d) show the coatings on top and the substrate on the bottom.

Metallurgical cross-sections from these as-deposited coatings of TWA Al, HVOF Al, flame-sprayed 316L powder, and HVOF 316L are shown in Fig. 3, a through d, respectively. The porosity of the coatings are determined by the straight line intercept method on these metallographs. In the comparison of the 316L coatings, where the starting material is identical, the higher velocities of an HVOF process appears to lower porosities by at least 50% if not by a factor of 2. In the case of the Al coatings, the porosity decreased by 3.5x to 5x. Low porosity coatings from an HVOF process is expected to be easier and quicker to finish to a smooth surface.

Vickers micro-hardnesses are measured on metallurgical cross-sections. A 10 gr load is used and each measurement is an average of five indentations. As a hardness reference, the micro-hardness of the 1020 mild steel substrate, away from the bead-blasted interface, is 196 ± 6 VHN. In comparison with the tabulated values, thermal sprayed Al is softer than all the steels, and thermal sprayed 316L is harder than mild steel. Hardness measurements can not obtained in the case of the twin-wire arc deposited Al because of the high degree of porosity. The hardness values indicate that the HVOF Al would be the easiest to post-coat finish. The assumption is also made that TWA deposited Al would also be amenable to a post-coat finish process.

After consideration of the data at this juncture, the HVOF Al coating is the preferred material and process because the coating has a smooth surface, the lowest porosity, and the lowest hardness. Since the estimated cost of an HVOF process is expected to be higher than a conventional thermal sprayed process, studies are conducted in parallel on the post-coat treatment of the other thermal spray processes.

Post-coat Treatments

Post-coat treatments of the as-deposited surfaces are performed in an attempt to achieve surfaces that would satisfy the Level 100 cleanliness requirement with contact verification. Mechanical treatments of brushing, sanding and bead blasting are tried. Wire brushing is abandoned quickly because it has no effect on the smoothness of the hard 316L surfaces and it smears the surfaces of the soft Al coatings.

Sanding the surfaces of the TWA Al coatings reduce the roughnesses (Fig. 4). A hand-held orbital sander is used, initially with 220 grit paper for 15 min over a 1 sq ft sample. The final finish is obtained with 320 grit paper, going over smaller portions of the sample in fifteen minute intervals. The roughness appears to reach a lower limit below a Ra of 50 μinches, where Ra is the arithmetic average of the surface deviations from the mean. The coating thicknesses are measured after the various sanding intervals and are co-plotted in Fig. 4. The roughness is decreasing along with the coating thickness. One proposal is the application of a thicker coating by the economical TWA process before sanding the surface. The logic is that an extra 0.009 inches would allow the sander to attain a roughness below 50 μinches but still have sufficient remaining thickness for a corrosion barrier.

Figure 4 Sanding of Al coatings from different deposition processes. Surface roughness can be achieved as low as 50 μinches.

Sanding the HVOF Al coating produces a Ra roughness of 166 ± 42 µinches at a rate of 5 min/sq ft. This demonstrates the advantage of a low porosity coating. Sanding a low porosity coating does not reveal new pores which must be removed with additional treatment. The thickness of the HVOF Al coating decreased only by 8% to reach this level of smoothness, compared to 61% by the TWA coating. The surface morphology of a sanded HVOF Al coating is shown in Figure 5.

Figure 5 Morphology of sanded HVOF Al coating

An alternative to sanding a porous coating is bead-blasting the surface. Although the bead-blasting process is not optimized, it did demonstrate that densification of porous coatings is possible without tearing the coating away from the substrate. Figure 6, a through c, shows bead-blasted surfaces of flame-sprayed Al with small diameter beads, flame sprayed Al with large diameter beads, and bead-blasted HVOF Al. Table 2 shows surface roughnesses achievable on the bead-blasted Al surfaces. The observation that the HVOF Al coating produced a smoother surface supports the hypothesis that the combination of a high velocity thermal spray and small diameter source material tends to produce a superior coating for cleanliness purposes.

Figure 6 Bead-blasted surfaces of thermal-deposited Al. (a) 0.005" diameter beads applied at 100 psi on Twin wire arc Al showed little densification; (b) 0.015" diameter beads applied at 60 psi on Twin wire arc Al reduced the coating porosity; (c) 0.002" diameter beads applied on HVOF Al.

Table 2 Surface roughness of bead-blasted thermal sprayed Al.

Al Coating Deposition Process	Bead Diameter (mils)	Surface Roughness (µinches)
Twin Wire Arc	5	446 ± 89
Twin Wire Arc	15	611± 297
HVOF	2	218 ± 43

Other treatments were chemical etching of the asperities away, re-flow of the coating via a welding torch.

CONCLUSIONS

This report compares the porosity, roughness, and hardness of coatings produced by twin-wire arc, flame-spray, and HVOF deposition tools. Al coatings are deposited by a twin-wire arc and a HVOF process. Stainless steel coatings are deposited by a flame-spray and a HVOF process.

The feasibility of Al deposition using an HVOF process has been demonstrated.

Bead-blasting reduces the porosity of the Al thermal sprayed coatings.

From the preliminary effort in this study, the HVOF Al appears to have the most potential of meeting the cleanliness Level 100 requirements. A post-coat finishing treatment is necessary. The coating porosity and the hardness is low relative to the other coating alternatives.

FUTURE WORK

Increase the productivity of the HVOF Al process to cover 37,000 square feet.

The HVOF Al coating must be tested for particulate generation in the presence of the laser light sources.

The HVOF Al coating must be tested for particulate generation during the precision cleaning with high-pressure (2500 psi) water rinse.

Optimize the post-coat finishing of the HVOF Al coating to meet the Level 100 cleanliness requirements and with contact validation. This may be a process as simple as sanding, bead-blasting, or a combination of the two because of the inside corner geometry in some of the steel frames.

A feasibility study of twin-wire arc Al with combined post-coat treatments of bead blasting, and sanding to achieve the cleanliness levels may be started as a back-up coating alternative.

Acknowledgments

The authors thank the following for their technical contributions towards the thermal spray project Mike Benapfl, Bob Kershaw, Ed Lindsey, Chris Steffani, Bob Vallier.

Auspices

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References

1. G. Deis, Requirements for interior surfaces of beam path components to preserve the optical performance over the life of NIF, NIF-0039493, 30 Nov 1999.
2. F. Genin, J. Menapace, A. Burnham, and I. Stowers, Final technical recommendation regarding the coatings for NIF internal steel structures, NIF-0010123, 2 June 1998.
3. F. Genin, J. Menapace, and J. Yoshiyama, Damage thresholds of painted and coated steel, and other metals at 1064 nm (10-ns); do not use paint of structures close to above medium fluence areas, NIF-0004472, Jan. 15, 1998.
4. G. Edwards, Precision High-Pressure Water Wash for NIF Components, NIF-5001323, (MEL98-008), 2 Sept 1999.
5. S. Jain, Surface Cleanliness Validation by Swiping for NIF Components, NIF-5002426 (MEL98-012), 2 June 1999.

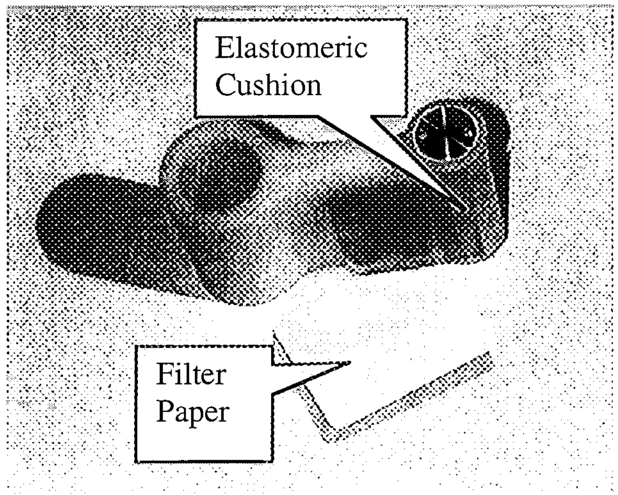

Figure 1 Fixture developed by LLNL to perform cleanliness verification. The fixture provides a method of holding the filter paper while folded around an elastomeric cushion approximately 6 mm wide and 50.8 mm long.

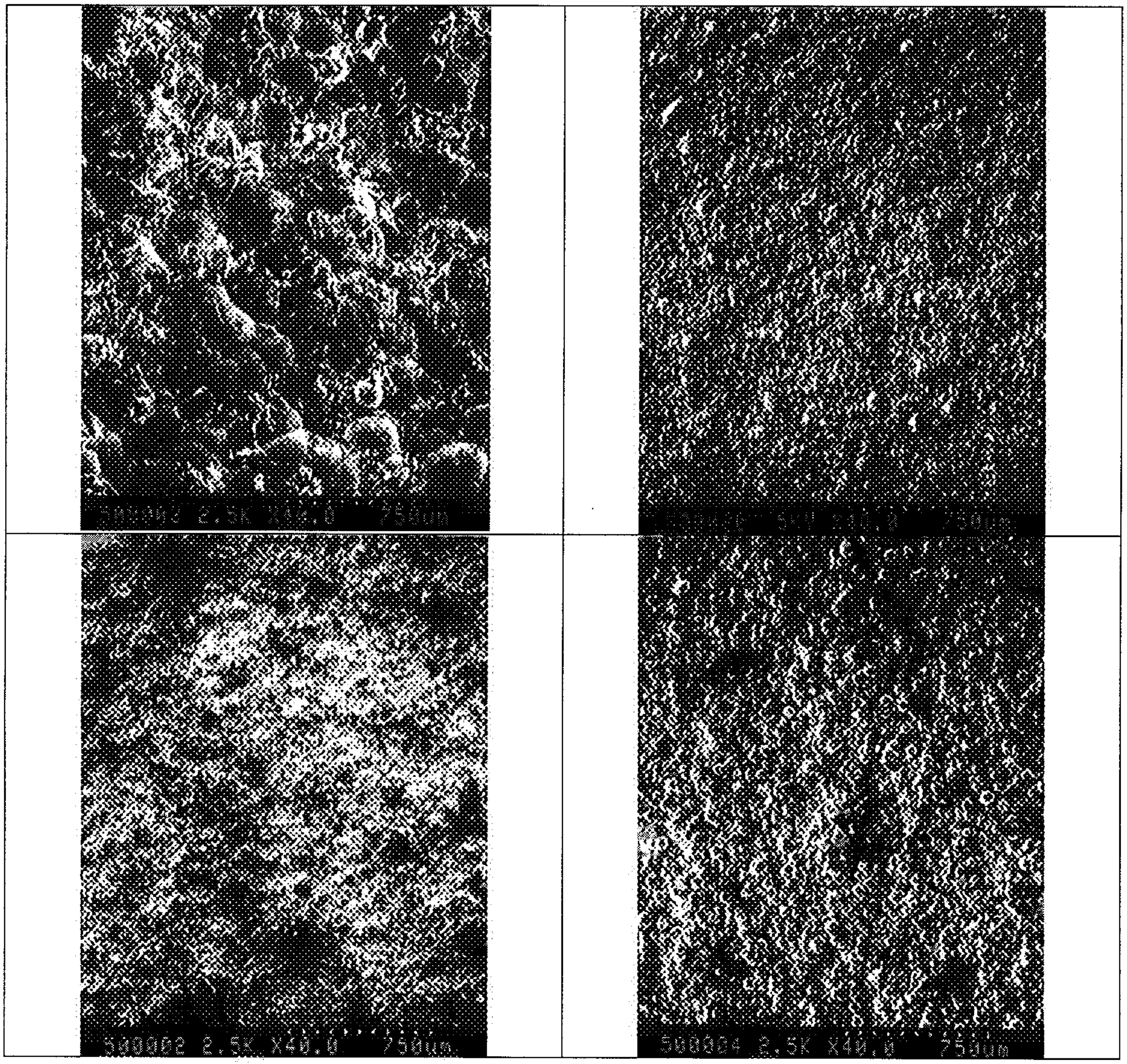

Figure 2 As-deposited surface morphology from (a) Twin wire arc Al wire, 0.125" diameter; (b) HVOF of Al powder; (c) Flame-sprayed 316L stainless steel powder; (d) HVOF of 316L stainless steel powder.

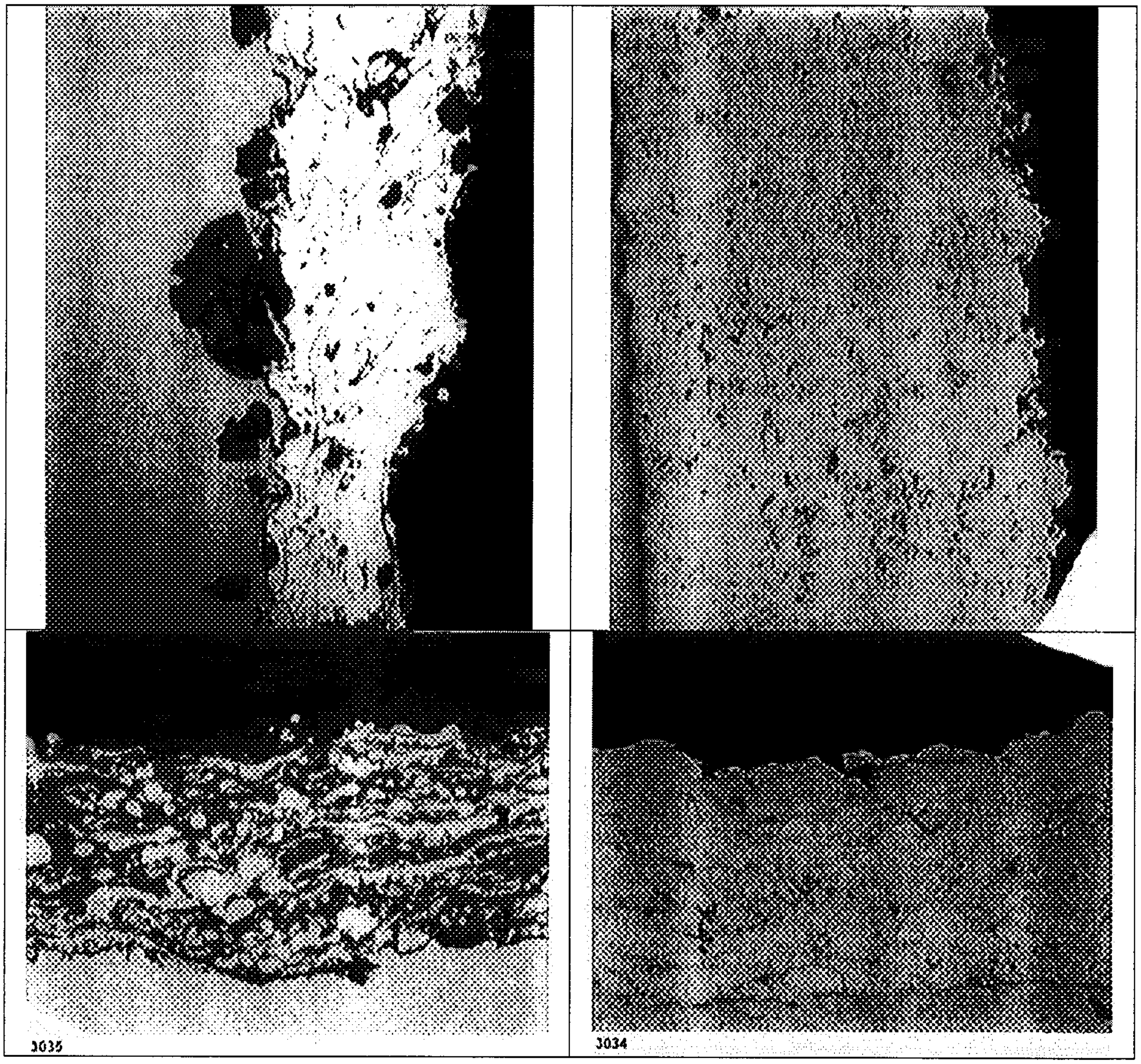

Figure 3 Metallurgical cross-sections of (a) Twin wire arc coating, 0.007" thick, from Al wire, 0.125" diameter; (b) HVOF coating, 0.015" thick, from Al powder; (c) Flame-sprayed coating, 0.010" thick, from 316L stainless steel powder; (d) HVOF coating, 0.012" thick, from 316L stainless steel powder. Panels (a) and (b) have the coating on the right and the substrate on the left. Panels (c) and (d) show the coatings on top and the substrate on the bottom.

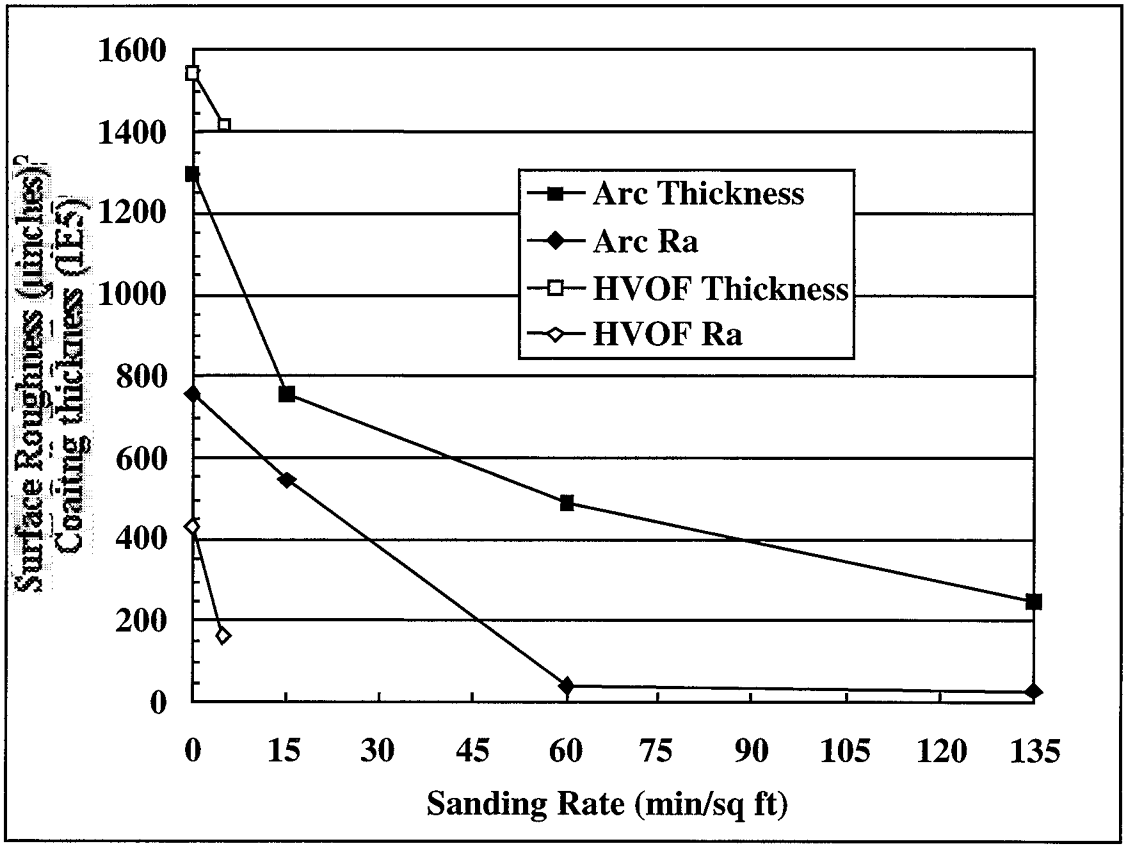

Figure 4 Sanding of Al coatings from different deposition processes. Surface roughness can be achieved as low as 50 µinches.

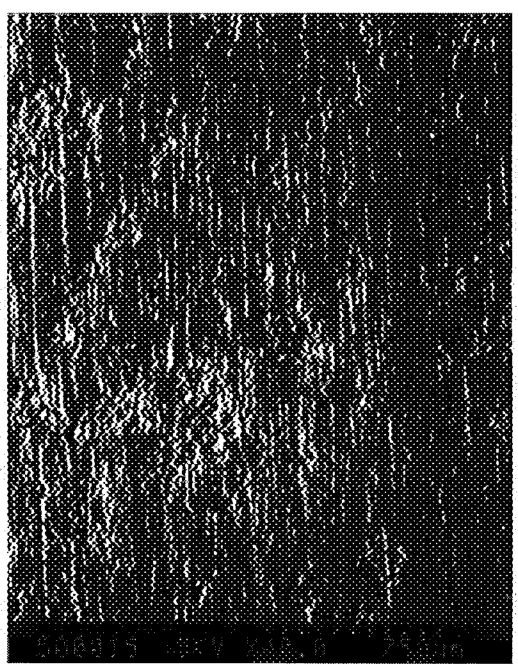

Figure 5 Morphology of sanded HVOF Al coating

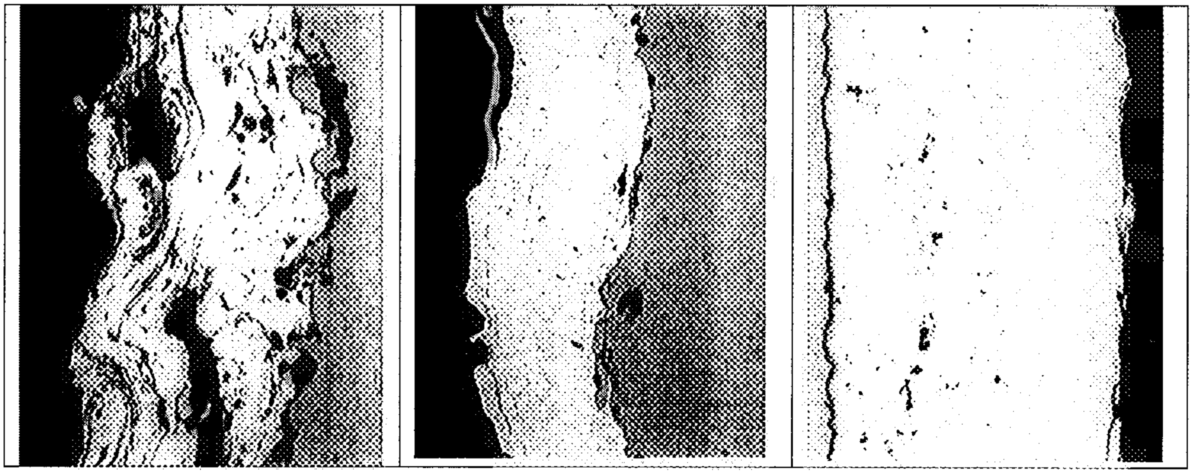

Figure 6 Bead-blasted surfaces of thermal-deposited Al. (a) 0.005" diameter beads applied at 100 psi on Twin wire arc Al showed little densification; (b) 0.015" diameter beads applied at 60 psi on Twin wire arc Al reduced the coating porosity; (c) 0.002" diameter beads applied on HVOF Al.